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Particle Collection by a Pilot Plant Venturi Scrubber Downstream From a Pilot Plant Electrostatic Precipitator

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16. ABSTRACT

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Dust	Stationary Sources	11G
Aerosols	Particulate	07D
Scrubbers	Venturi Scrubbers	07A, 13I
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PARTICLE COLLECTION BY A PILOT PLANT VENTURI SCRUBBER DOWNSTREAM FROM A PILOT PLANT ELECTROSTATIC PRECIPITATOR

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Abstract – The results of pilot plant experiments of particulate collection by a venturi scrubber downstream from an electrostatic precipitator (ESP) are presented. The data, which cover a range of scrubber operating conditions and ESP efficiencies, show that particle collection by the venturi scrubber is not affected by the upstream ESP; i.e., for a given scrubber pressure drop, particle collection efficiency as a function of particle diameter is the same for both ESP on and ESP off. The experimental results are in excellent agreement with theoretical predictions. Order of magnitude cost estimates indicate that particle collection by ESP scrubber systems may be economically attractive when scrubbers must be used for SO_x control.

INTRODUCTION

There are numerous undocumented reports that extremely low particle mass emissions can be obtained from relatively low pressure drop scrubbers downstream from moderately efficient electrostatic precipitators (ESPs). The recent revision of the U.S. New Source Performance Standards which require scrubbers for SO_2 on most utility boilers has increased the interest of both EPA and utilities in these undocumented reports. If the reports are true, then it might be possible to reduce the total cost required to meet both the SO_2 and particulate emission standards by proper system design.

Unfortunately, the data on the performance of ESP scrubber systems are insufficient. Thus a pilot plant experimental study was undertaken by the Particulate Technology Branch of EPA's Industrial Environmental Research Laboratory at Research Triangle Park, North Carolina, to provide the necessary experimental data. Also a theoretical study was conducted to determine what ESP scrubber configurations would be capable of providing 99.7% overall mass efficiency on a typical fly ash particle size distribution. A mass efficiency of 99.7% is required to meet the particulate emission New Source Performance Standard for Utility Boilers of 13 ng J^{-1} (0.03 lb/10^6 Btu) for typical fly ash with a margin of safety. An order of magnitude cost study was also undertaken.

The objectives of the program were to:

(1) Determine the effect of an ESP on the particle penetration (1 minus efficiency) of a venturi scrubber as a function of particle diameter characteristics.
(2) Determine the overall mass penetration and particle penetration as a function of particle diameter for the ESP scrubber system.
(3) Determine, with the aid of mathematical models, the ESP scrubber configurations capable of meeting an emission standard for fly ash of 13 ng J^{-1}.
(4) Estimate order of magnitude costs for the systems in objective (3), above.

THEORY

The theoretical study and the experimental study were conducted in parallel. Because there was no reason to expect that the low levels of particle charge exiting the ESP would affect particle collection by uncharged drops (Sparks, 1971), Calvert's venturi model (as programmed by Sparks (1978) and modified for this study to accept histogram particle size distributions) was used to model the venturi scrubber. This model was chosen because Harmon and Sparks (1979) have shown that the performance predicted by this model is in excellent agreement with data from full scale scrubbers. ESP performance was modeled by the EPA/Southern Research Institute computer model for electrostatic precipitation, Revision I (McDonald, 1978). Two cases were examined:

—A low current density case which corresponds to a fly ash with high electrical resistivity (~5×10^{11} ohm cm) such as produced by low sulfur coal (< 1% S).
—A moderate current density case which corresponds to a fly ash with moderate electrical resistivity (~3×10^{10} ohm cm) such as produced by moderate sulfur coals (~1.5–2.5%).

The following assumptions were made:

(1) The fly ash size distribution entering the ESP was lognormal with mass mean diameter of 20 μm and geometric standard deviation of 4.5.
(2) Fly ash density was 2.4 g cm^{-3}.
(3) Gas flow distribution in the ESP was characterized by

Table 1. Summary of calculated results for ESP scrubber system

Configuration ID number	ESP parameters			Scrubber parameters		
	SCA $m^2\,Am^{-3}s^{-1}$	$\overline{Pt}$	Resistivity	ΔP cm water	$\overline{Pt}$	Overall penetration
1	156.1	0.0024	High	—	—	0.0024
2	78.04	0.0165	High	9.1	0.182	0.003
3	33.93	0.0771	High	24.0	0.0389	0.003
4	16.43	0.187	High	34	0.016	0.003
5	8.214	0.330	High	43	0.009	0.003
6	74.32	0.002	Moderate	—	—	0.002
7	35.47	0.0164	Moderate	8	0.183	0.003
8	15.30	0.0762	Moderate	24	0.0394	0.003
9	7.094	0.186	Moderate	34	0.016	0.003
10	3.393	0.331	Moderate	43	0.0091	0.003
11	—	—	—	67	0.0029	0.003

a normalized standard deviation of 0.25.

(4) The factor for sneakage and nonrapping reentrainment in the ESP was 0.1.

(5) Rapping losses were typical as described by McDonald (1978).

(6) Particulate mass concentration entering ESP was 6.7 g Am^{-3} at 150°C.

The theoretical study was conducted by determining the overall mass penetration and penetration as a function of particle diameter (the graded penetration) for a variety of ESP collection plate areas for the two current densities. The graded penetration curves and the ESP inlet particle size distribution curve were then used to construct an ESP outlet particle size distribution curve. This particle size distribution curve was then used as the scrubber inlet particle size distribution curve. It was then possible to use the scrubber model to determine the pressure drop required to give a total ESP scrubber system mass penetration of 0.03. The scrubber model also gave the system outlet particle size distribution and the scrubber graded penetration curve.

THEORETICAL RESULTS

The results of the calculations are summarized in Table 1; they show that the scrubber pressure drop, ΔP, needed for a system penetration of 0.03 is a function of the penetration through the ESP, Pt_{ESP}, and is essentially independent of the current density. The pressure drop to $\overline{Pt}_{ESP}$ relationship is:

$$\Delta P = 85\,\overline{Pt}_{ESP}. \quad (1)$$

where ΔP is in cm water and $\overline{Pt}_{ESP}$ is a fraction.

Because the specific collector area, SCA, required to give a given $\overline{Pt}_{ESP}$ is a function of the current density, the relationship between ΔP and SCA is different for the two current densities:

For the high current density case,

$$\Delta P = \exp(3.94 - 0.0536\,SCA); \quad (2)$$

For the low current density case,

$$\Delta P = \exp(3.90 - 0.0220\,SCA). \quad (3)$$

For both, ΔP is in cm water and SCA is in $m^2\,Am^{-3}$. $1\,Am^3 \equiv 1$ actual cubic meter.

The calculated results show that the SCA can be reduced by about a factor of 2 for both moderate and high resistivity cases, for a scrubber ΔP of about 10 cm water.

DISCUSSION OF THEORETICAL RESULTS

The initial reaction to the calculated results is one of disbelief. It does not appear reasonable to expect a fairly inefficient ESP and a moderate to low pressure drop scrubber to perform as well as both the experimental data and the calculated results show. An examination of the particle penetration vs particle diameter curves (the graded penetration curve) for both devices acting alone and the combined graded penetration curve can explain the results.

The calculated graded penetration curve for an ESP with a penetration of 0.0771 is shown in Fig. 1. Note that the ESP curve has a broad peak from about 0.4 to 1 μm and then drops fairly rapidly on both sides of the

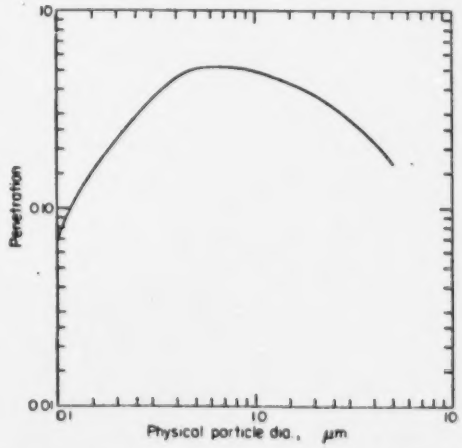

Fig. 1. Calculated penetration (fraction) vs particle diameter (μm) for ESP collecting typical fly ash—ESP mass penetration = 0.0771.

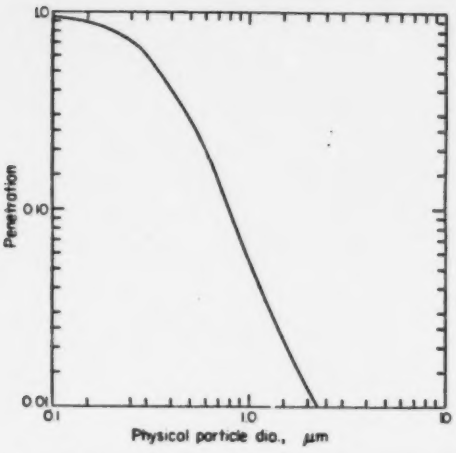

Fig. 2. Calculated penetration (fraction) vs particle diameter (μm) for scrubber collecting typical fly ash—scrubber pressure drop = 23 cm H_2O.

peak. On the other hand the graded penetration curve, Fig. 2, for a scrubber needed to produce an emission of 13 ng J^{-1} in combination with the ESP drops rapidly from essentially 1.0 at 0.1 μm to less than 0.01 at 3 μm. The scrubber is seen to be efficient in particle diameter regions where the ESP is inefficient and the ESP is efficient in particle diameter regions where the scrubber is inefficient. The two devices complement each other.

The graded penetration of the ESP scrubber system can be obtained by multiplying the two separate graded penetration curves; i.e.,

$$Pt(d)_{ESPS} = Pt(d)_{ESP} \times Pt(d)_S \qquad (4)$$

where $Pt(d)_{ESPS}$, $Pt(d)_{ESP}$, and $Pt(d)_S$ are the penetrations of particles with diameter d for the ESP scrubber system, the ESP alone, and the scrubber alone, respectively. The resulting graded penetration curve is shown in Fig. 3. Note the curve has a sharp peak at about 0.3 μm and drops rapidly on both sides. This sharp peak is characteristic of the ESP scrubber system and, as is discussed below, may cause problems with respect to plume opacity limits.

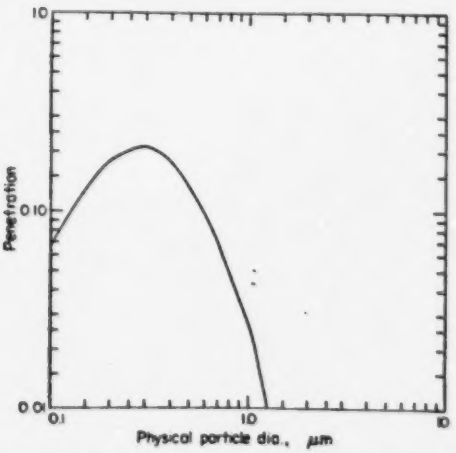

Fig. 3. Calculated penetration (fraction) vs particle diameter (μm) for ESP scrubber system with ESP characteristics as shown in Fig. 1 and scrubber characteristics as shown in Fig. 2—system mass penetration = 0.003.

The calculated results and experimental results discussed later demonstrate that it is impossible to understand what is happening in particle collection devices without particle size data.

PLUME OPACITY

Theoretical calculations of in-stack light transmittance (1 minus the plume opacity) as measured by a transmissometer are inexact due to lack of data on particle refractive index and other parameters, especially the particle size distribution. However, useful estimates can be made based on the work of Ensor (1972).

The in-stack plume opacity is a function of the particle size distribution, the refractive index of the particles, the particle concentration, and the optical path length. Ensor (1972) has shown that the in-stack light transmittance is given by

$$\ln(I/I_0) = \frac{WL}{K\rho}, \qquad (5)$$

where

- I is the intensity of the light transmitted through the aerosol;
- I_0 is the intensity of the light source (I/I_0 is the transmittance);
- W is the mass concentration of particles;
- L is the optical path length, which is usually the stack diameter;
- K is a parameter which depends on the particle size distribution;
- ρ is the particle refractive index, and the wavelength of light is the particle density.

A plot of K for a lognormal particle size distribution vs geometric mass mean radius with geometric standard deviation as a parameter for wavelength of light = 550 nm and a refractive index = 1.50 is shown in Fig. 4.

The calculated graded penetration curves for the ESP, scrubber, and ESP scrubber system can be used to estimate the lognormal parameters for various system configurations that meet the 13 ng J^{-1} emission limit. These lognormal parameters can then be used to estimate K from Fig. 4. The light transmittance can then be calculated from

$$I/I_0 = \exp(-WL/K\rho). \qquad (6)$$

We will assume

$W = 0.02\ \text{g Am}^{-3}$

(roughly equivalent to 13 ng J^{-1}),

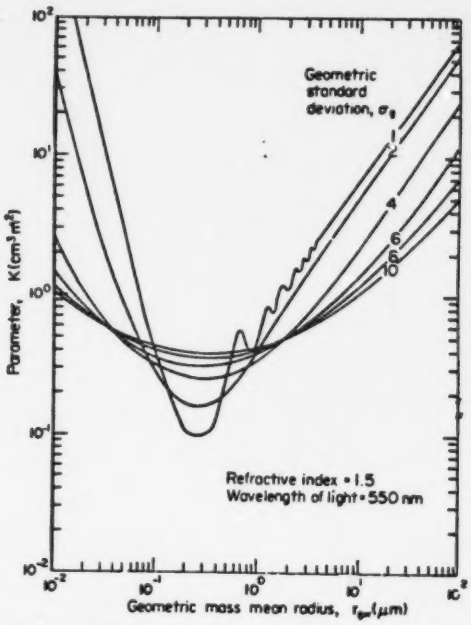

Fig. 4. Calculated values of parameter K as a function of lognormal size distribution parameters for white aerosol.

$L = 10$ m,
$\rho = 2.4$ g cm^{-3}.

The estimated light transmittance for each of the system configurations in Table 1 is shown in Table 2. Because the particle size distributions of the ESP scrubber system are essentially the same for both the moderate and high resistivity cases when the ESP penetration is constant, only results for the high resistivity cases are shown.

The estimates of transmittance show that the ESP scrubber system can have considerably lower transmittance (higher opacity) than either the ESP-only system or the scrubber-only system.

It must be noted that these calculations of transmittance are subject to large uncertainties; e.g., the calculated outlet size distributions are not exactly lognormal. The ESP computer model predictions of graded penetration curves are not well confirmed with experimental data. Slight changes in the non-ideal factors in the ESP model can have a large effect on the predicted outlet size distribution, which will affect the calculated transmittance.

In spite of the uncertainties in the calculations, the fact that ESP and scrubbers operate on the particle size distribution differently will tend to make the outlet particle size distribution finer and more monodisperse. This tendency to make a fine monodisperse outlet particle size distribution should cause higher opacities for a given mass emission. And, in fact, Sparks (1979) has reported that such a situation exists at one full scale ESP scrubber system used to control particulate emissions from a utility boiler.

EXPERIMENTAL EQUIPMENT

The pilot scale scrubber system tested in conjunction with the pilot ESP system consisted of a venturi scrubber, an entrainment separator, and a blower and motor. The venturi scrubber had a round cross section with a throat length of 25.4 cm. The throat section could be removed so various throat diameters could be tested. The ESP scrubber tests involved only two throat diameters: 7.62 and 10.16 cm. Larger diameters could not be installed due to the limiting size of the opening at the throat bottom flange. The water was added tangentially at two points at the top of the scrubber. The water flow rate could be varied up to a maximum of 6.43 $\times 10^{-2}$ m^3 min^{-1}. The scrubbing water was not recirculated. Maximum gas flow was about 28 m^3 min^{-1}.

Following the venturi scrubber, the gas stream entered a cyclonic entrainment separator. The separator had a diameter of 50.8 cm and was 1.22 m in height. The gas entered the separator at the bottom and exited tangentially near the top. The gas was moved through the system by a blower powered by a 15 hp motor.

The installation of the scrubber to the outlet of the ESP involved removing a 3 m section of duct from the ESP system and rerouting the gas stream through the scrubber system and back to the original ESP system duct, as shown in Fig. 5. A transition section was added to the ESP duct to reduce the duct diameter from 30.48 to 15.24 cm to accommodate the scrubber. A flexible duct was used to connect the transition section to the scrubber. The gas was exhausted from the entrainment separator through a 15.24 cm duct to the fan and through a flexible duct (30.48 cm diameter) to connect the fan to the original ESP exhaust system.

Pressure taps were added to the duct at the entrance to the scrubber, between the scrubber and separator, and at the exit of the separator. The pressure taps allowed for measurement of pressure drop over the scrubber and separator.

The ESP used for the experiment is a one lane wire duct ESP and is described by Lawless *et al.* (1979).

Table 2. Estimated light transmission and in-stack plume opacity for ESP scrubber systems based on calculated results*

Configuration† ID number	System	Transmission, I/I_0	Opacity, $1 - I/I_0$
1	ESP alone	0.85	0.15
2	ESP and scrubber	0.63	0.37
3	ESP and scrubber	0.70	0.30
4	ESP and scrubber	0.73	0.27
5	ESP and scrubber	0.76	0.24
11	Scrubber alone	0.80	0.20

* All systems produce calculated outlet emission of 0.02 g Am^{-3}.
† Configuration ID number refers to Table 1.

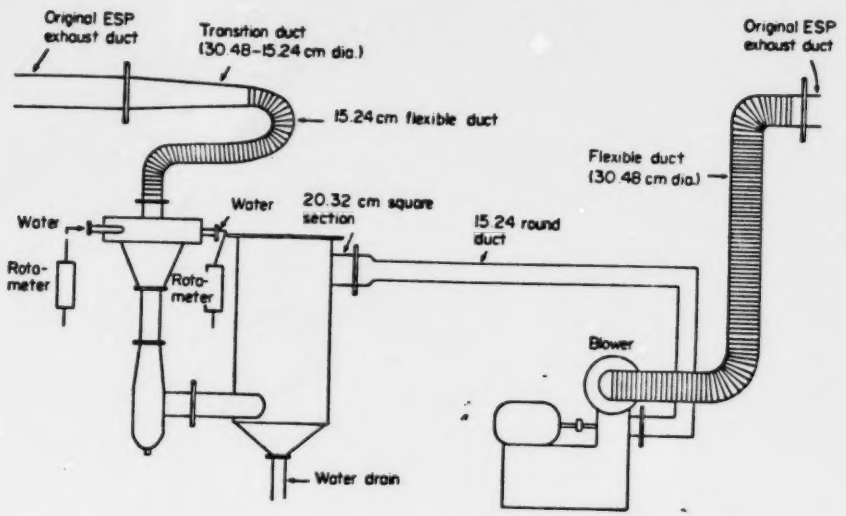

Fig. 5. Drawing showing how pilot plant was added to EPA pilot plant ESP for experimental study.

The aerosol generator consisted of two sand blast guns which were fed fly ash by a vibrating screw feeder. A cyclone was placed in the line between the feeder and the sand blast guns, to remove large particles and thus prevent duct fallout in the inlet duct. Previous experience showed that this aerosol generator was stable. Additional information can be found in Lawless *et al.* The particle size distribution was approximately lognormal with a geometric mass mean diameter of about 5.5 μmA and geometric standard deviation of 2.3 when the cyclone was used.

All size distribution measurements were made with Meteorology Research, Inc. (MRI) cascade impactors with greased substrates. The impactors were calibrated by personnel of EPA Industrial Environmental Research Laboratory's Particulate Technology Branch, using the procedure described by Calvert *et al.* (1976).

TEST PROGRAM

The experimental program was divided into two phases: Phase 1 was a preliminary study, and Phase 2 was a systematic study with replication. The variables studied in the Phase 2 experiments were:

—ESP on or off;
—ESP penetration 1 to 0.037 (efficiency 0 to 96.3%);
—Liquid/gas ratio 6.65×10^{-4} to 2.66×10^{-3} m^3 Am^{-3}.

The experimental conditions for all tests are shown in Table 3.

Table 3. Experimental conditions and overall results for pilot plant ESP scrubber experiments

		Scrubber parameters				
Date	ESP penetration	Throat diameter, cm	L/G, m^3 m^{-3}	ΔP, cm H_2O	Penetration	Overall penetration for system
17 Dec. 77	0.05	10.16	1×10^{-3}	31.1	0.0226	0.00113
18 Dec. 77	ESP off	10.16	1×10^{-3}	31.1	0.022	0.022
19 Dec. 77	0.034	10.16	1×10^{-3}	31.1	0.024	0.000816
16 Jan. 78	0.382	10.16	1.2×10^{-3}	39.6	0.0129	0.0049
17 Jan. 78	0.34	10.16	1.2×10^{-3}	39.6	0.0165	0.0056
19 Jan. 78	ESP off	10.16	1.2×10^{-3}	39.6	0.0106	0.0106
23 Jan. 78	ESP off	10.16	1.2×10^{-3}	39.6	0.010	0.010
24 Jan. 78	ESP off	10.16	2.3×10^{-13}	68.3	0.0022	0.0022
25 Jan. 78	ESP off	10.16	2.3×10^{-3}	68.3	0.0020	0.0020
26 Jan. 78	0.328	10.16	2.3×10^{-3}	68.3	0.0034	0.0011
27 Jan. 78	0.516	10.16	2.3×10^{-3}	68.3	0.004	0.0021
3 Feb. 78	ESP off	7.62	1.2×10^{-3}	62.2	0.0041	0.0041
6 Feb. 78	ESP off	7.62	1.2×10^{-3}	62.2	0.0048	0.0048
7 Feb. 78	0.257	7.62	1.2×10^{-3}	62.2	0.0072	0.0018
8 Feb. 78	0.256	7.62	1.2×10^{-3}	62.2	0.0079	0.0020
14 Feb. 78	ESP off	10.16	5.32×10^{-4}	26.7	0.0235	0.0235
15 Feb. 78	ESP off	10.16	5.32×10^{-4}	26.7	0.019	0.019
21 Feb. 78	0.733	10.16	5.32×10^{-4}	26.7	0.0138	0.010
23 Feb. 78	0.0375	10.16	5.32×10^{-4}	26.7	0.0911	0.0034

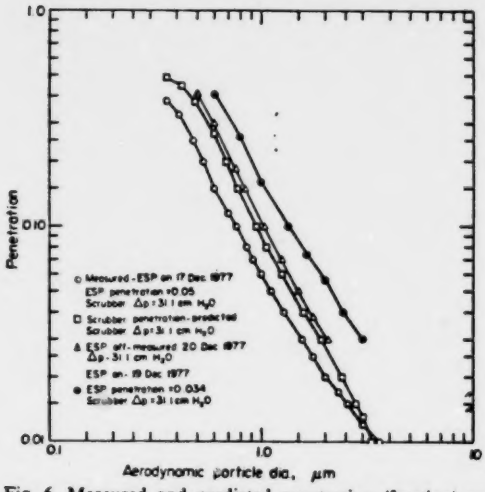

Fig. 6. Measured and predicted penetration (fraction) vs particle diameter (μm) for pilot plant venturi scrubber—Phase 1 experiments.

EXPERIMENTAL RESULTS AND DISCUSSION

The overall mass penetrations for the ESP, the scrubber, and the ESP scrubber system are shown in Table 3. Note the low overall mass penetration which is in line with the theoretical results discussed earlier. As discussed earlier these overall penetration results cannot be properly interpreted without knowledge of the graded penetration curves.

The measured graded penetration curves for the scrubber under Phase 1 conditions are shown in Fig. 6 as a plot of penetration vs aerodynamic particle diameter, d_A. ($d_A = d\sqrt{\rho C}$ where d is the physical particle diameter, ρ is the density of the particle, and C is the Cunningham correction factor.) The predicted graded penetration curve is also shown in Fig. 6. The average graded penetration curves for each of the Phase 2 tests are shown in Fig. 7.

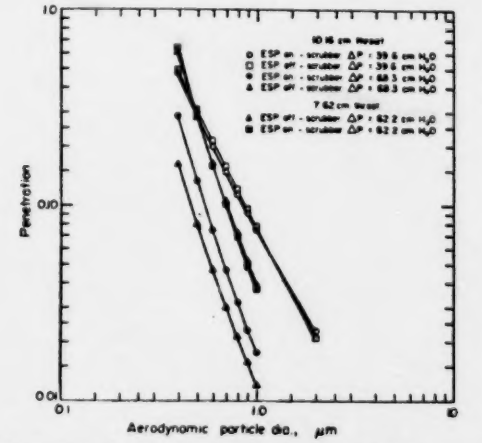

Fig. 7. Measured penetration (fraction) vs particle diameter (μm) for pilot plant venturi scrubber—Phase 2 experiments.

It is obvious from the data shown in Figs 6 and 7 that scrubber performance is dominated by the pressure drop across the scrubber and that the ESP has no effect on the performance of the scrubber. It is also clear from Fig. 2 that the predicted graded penetration curve is in excellent agreement with the experimental data. Thus the hypothesis used in the theoretical study is verified; i.e., the small electrical charge on the particles exiting the ESP does not affect particle collection in the scrubber.

Statistical analysis of the data showed that:

(1) There was no effect on scrubber performance due to the ESP.
(2) Particle collection in the venturi was dominated by pressure drop.
(3) Changes in throat diameter (i.e., changes in gas velocity in the throat) had more effect than changes in L/G.
(4) The estimated standard deviation in the experimental graded penetration curves was about 20%.

The experimental graded penetration curves for the ESP scrubber system do not show the peak in penetration because data for particle diameters less than about 0.7 μmA are not available due to limitations of cascade impactors.

The fact that the scrubber model predicts the graded penetration curves for full scale scrubbers where water is recirculated and the graded penetration curves for this study where water was not recirculated indicates that water recirculation does not affect particle collection in well designed systems.

COST ANALYSIS

A detailed cost analysis is necessary to determine if the tradeoff between pressure drop and SCA is justified. However, an order of magnitude analysis can be undertaken to determine if detailed analysis is justified.

The order of magnitude cost analysis involves the following assumptions:

(1) The total turnkey capital cost of a cold-side ESP is \$320 m^{-2} plate area. (A rough range of total turnkey cost is \$270–\$370 m^{-2}.)
(2) There is no capital cost of the scrubber because it is needed for SO_x control.
(3) Fan efficiency is 60%.
(4) Electricity cost is \$0.02 kWh^{-1}.
(5) Annualized capital charges are 15% of total turnkey capital cost.
(6) Plant operates 6100 h y^{-1} (70% capacity).
(7) ESP operating and maintenance costs are insignificant compared with capital costs of ESP and can be neglected.
(8) Scrubber maintenance and liquid loop costs are not included because they are needed for the SO_x system.
(9) Costs are for 1 MW which produces 5440 Am^3 h^{-1} flue gas.

With these assumptions the total annualized cost per MW is given by:

$$AC = Q\left[4.38 \times 10^{-3} HK_e \frac{\Delta P}{15.8E}\right] + 0.15\,CC, \quad (7)$$

where

AC is the annualized cost;
Q is the flow rate in $Am^3\,h^{-1}$;
H is the number of operating hours y^{-1};
K_e is the cost of electric power in $\$\,kW\,h^{-1}$;
ΔP is the scrubber pressure drop in cm H_2O;
E is the fan efficiency;
CC is the capital cost in \$;
4.38×10^{-3} and 15.8 are unit conversion constants.

For a 1 MW plant:

$Q = 5440\,Am^3\,h^{-1}$;
$H = 6100\,h$;
$K_e = \$0.03$;
$E = 0.60$;

$$CC = \frac{320 \times SCA \times Q}{3600},$$

where SCA is the specific collector area in $m^2\,s\,Am^{-3}$, and 3600 is necessary to convert $Am^3\,h^{-1}$ to $Am^3\,s^{-1}$.

The calculations discussed previously showed that for the moderate resistivity case

$$\Delta P = \exp(3.94 - 0.0536\,SCA),$$

and for the high resistivity case

$$\Delta P = \exp(3.90 - 0.022\,SCA).$$

The cost equation for the moderate resistivity case is:

$$AC = 5440\frac{[4.38 \times 10^{-4} \times 6100 \times 0.03\exp(3.94 - 0.0536)]}{15.8 \times 0.6} + \frac{0.15 \times 320}{3600} SCA. \quad (8)$$

The SCA for minimum cost can be obtained by solving $dAC/dSCA = 0$ for SCA. For the moderate resistivity case $SCA_{min} = 10.7\,m^2\,Am^3\,s^{-1}$. For the high resistivity case the only change is in the exponential term and

$$SCA_{min} = -0.37\,m^2\,s\,Am^{-3}.$$

In other words the scrubber alone is the minimum cost option. The calculated cost for the moderate resistivity case is:

$$\$2.1 \times 10^3\,y^{-1}\,MW^{-1}.$$

The calculated cost for the high resistivity case is

$$\$2.3 \times 10^3\,y^{-1}\,MW^{-1}.$$

The maximum cost for the high resistivity case is for the ESP alone and is $\$11 \times 10^3\,y^{-1}\,MW^{-1}$. The maximum cost for the moderate resistivity case is also for the ESP alone and is $\$5 \times 10^3\,y^{-1}\,MW^{-1}$.

The cost picture is changed somewhat if a scrubber has to be purchased for particulate removal. In this case Equation (8) becomes

$$AC = 5440[8.46 \times 10^{-3}\exp(3.94 - 0.0536\,SCA) + 1.33 \times 10^{-2}\,SCA] + 0.15\,CC_{scrubber}$$

for the moderate resistivity case and

$$AC = 5440[8.46 \times 10^{-3}\exp(3.90 - 0.022\,SCA) + 1.33 \times 10^{-2}\,SCA] + 0.15\,CC_{scrubber}$$

for the high resistivity case. $CC_{scrubber}$ is the capital cost of a scrubber. Ensor *et al.* (1975) reported that the turnkey capital cost of a particulate scrubber system is $\$50\,kW^{-1}$ or $\$50{,}000\,MW^{-1}$. The annualized cost of the scrubber is $0.15 \times \$50{,}000 = \$7500$ which must be added to the minimum costs calculated earlier. The annualized cost for the moderate resistivity cases becomes $\$9600\,MW^{-1}\,y^{-1}$, which exceeds the cost of ESP alone. The annualized cost for the high resistivity case becomes $\$9800\,MW^{-1}\,y^{-1}$ which is still less than the cost of the ESP alone.

CONCLUSIONS

The results of the experimental and theoretical studies support the following conclusions:

(1) The performance of a venturi scrubber is not affected by the ESP; i.e., the particle penetration vs particle diameter characteristics of the scrubber are the same whether the ESP is on or off.
(2) The performance of the scrubber is adequately modeled by the SR-52 programmable calculator model described by Sparks (1978).
(3) An ESP scrubber system can achieve an emission of $13\,ng\,J^{-1}$.
(4) Annualized costs of an ESP scrubber system are attractive when compared to costs for an ESP alone for many cases.
(5) Plume opacity from an ESP scrubber system may be much higher for a given mass emission than the plume opacity from an ESP alone.

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